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Oyster (*Ostrea edulis*) extirpation and ecosystem transformation in the Firth of Forth, Scotland

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ABSTRACT

Marine inshore communities, including biogenic habitats have undergone dramatic changes as a result of exploitation, pollution, land-use changes and introduced species. The Firth of Forth on the east coast of Scotland was once home to the most important oyster (*Ostrea edulis* Linnaeus, 1758) beds in Scotland. 19th and early 20th century fisheries scientists documented the degradation and loss of these beds, yet transformation of the wider benthic community has been little studied. We undertook archival searches, ecological surveys and shell community analysis using radioisotope dated sediment cores to investigate the history of decline of Forth oyster beds over the last 200 years and the changes to its wider biological communities. Quadrat analysis of the present day benthos reveal that soft-sediment communities dominate the Firth of Forth, with little remaining evidence of past oyster beds in places where abundant shell remains were picked up by a survey undertaken in 1895. Queen scallops (*Aequipecten opercularis* Linnaeus, 1758) and horse mussels (*Modiolus modiolus* Linnaeus, 1758) were once common within the Forth but have also markedly decreased compared to the earlier survey. Ouranalyses of shell remains suggest that overall mollusc biomass and species richness declined throughout the 19th century and early 20th century, suggesting broader-scale community change as human impacts increased and as habitats degraded. Inshore communities in the Firth of Forth today are less productive and less diverse compared to past states, with evidence suggesting that most of the damage was done by early bottom trawling and dredging activities. Given the pervasive nature of intensive trawling over the past 150 years, the kind of degradation we document for the Firth of Forth is likely to be commonplace within UK inshore communities.

Introduction

Healthy biogenic habitats such as oyster (*Ostrea* spp., *Crassotrea* spp.), maerl (*Lithothamnion* spp.) and horse mussel (*Modiolus modiolus* Linnaeus, 1758) communities perform a variety of ecological functions including stabilisation of sediment, creation of feeding and nursery habitat for juvenile fish species, and water filtration (Holt et al. 1998). A reduction or loss of these organisms results in subsequent loss of ecosystem services (Jackson et al. 2001; Lotze et al. 2006; Roberts 2007). Yet many of these communities are under threat from a multitude of human impacts including destructive fishing methods, increased sediment loading, altered hydrodynamic regimes, disease and the introduction of non-native competitors and predators (Airoldi & Beck 2007; Hall-Spencer et al. 2003; Jackson et al. 2001; Lotze & Milewski 2004). Beck et al. (2011) estimated that globally, 85% of oyster reefs have been destroyed with many remaining beds degraded to the point where they have limited or no ecological function.

In many cases the long time-interval over which degradation has occurred makes it difficult to determine the original extent and/or nature of biogenic habitats prior to large-scale human influence and hence determine the true degree of degradation (Lotze et al. 2006; Robinson & Frid 2008). It is likely that many estuarine or coastal seas have suffered from the ‘shifting baseline syndrome’ (Dayton et al. 1998; Pauly 1995), where current generations (and consequently current management) underestimate the extent of changes to coastal areas and therefore fail to manage areas for recovery. Exceptions do exist; the San Francisco Estuary Institute is an initiative that aims to document and record past conditions and use the information to guide restoration management (Grossinger et al. 2005). However conservation-planning policies often make little or no reference to past conditions (Ban et al., in preparation).

Native oysters (*Ostrea edulis*) were once plentiful in open sea environments and inshore estuaries around the UK (Royal Commission 1885). Yet today few wild populations of native

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oysters exist (Hiscock et al. 2005); indeed, many oyster populations were severely degraded prior to 1900 (Royal Commission 1885). This is almost certainly the case for many other bottom-living communities, e.g. maerl and horse mussel reefs (Airoldi & Beck 2007; Hall-Spencer & Moore 2000), but their historical extent and distribution tends to be less well represented in the literature (Airoldi & Beck 2007) compared to oysters, which were a valuable fishery. Where archival information exists, historical research can help to infer previous baseline states for biogenic communities. However, using archival methods alone may limit our interpretation of change to the few species mentioned in historical documents. Hence, other methods must be employed to determine the past status of benthic communities as a whole and to verify timings and drivers of change. Edgar and Samson (2004) for example, used mollusc death assemblages and isotope dating techniques from sediment cores to describe changes in molluscan assemblages in Tasmania over a period of 120 years. Whilst the decline of scallops and oysters – the target of a commercial dredge fishery – had been well documented there, Edgar and Samson were able to show that the wider mollusc community had also declined over the same period, a decrease not previously reported in the fisheries literature.

Our study uses historical, ecological and radioisotope dating techniques to reconstruct the history of the benthic community of the Firth of Forth, including the now-extinct oyster population, and to determine the extent and drivers of change to the Forth's inshore environment over the course of the last two centuries. We qualitatively compare past habitat descriptions with present day field assessments of habitats using information sourced from 19th century Admiralty charts and past scientific surveys. Using mollusc shell remains taken from dated sections of sediment cores we analyse changes over time to the molluscan benthos. We argue that human activities, in particular destructive fishing methods and land-use changes, have transformed marine communities in the Firth of Forth to a much greater extent than is generally acknowledged today.

Methods

Historical records search and field site location

We searched local museums, university libraries, public archives and published government reports for literature on past Firth of Forth marine habitats. Two main sources of information: 19th century Admiralty charts and a report of a number of scientific dredge surveys performed in 1895 (Fulton 1896), were used to determine sites that used to contain extensive oyster beds, and hence were potentially suitable for comparative analysis. Older charts did not make reference to magnetic North, so we determined the location of past oyster fishing grounds by comparing the position of the marked ground in relation to at least two obvious landmarks present on the chart (e.g. a named rock or a headland). We then found the same landmarks on present charts and thus established the location of each site using triangulation. We determined the position of the dredged sites in the same way, but only selected locations for study that revealed high quantities of live oysters during the 1895 survey. We then further selected sites for analysis on the basis of their practical suitability for diving. Given that the Firth of Forth has a mean spring tidal range of 5.0 m and a mean neap tidal range of 2.5 m (Webb & Metcalfe 1987), with currents up to 1.5 knots, we excluded from consideration sites that were unsuitable due to factors such as depth, strong currents, high shipping traffic or distance from a launch site. Sites likely to have been substantially altered by navigational dredging were also discounted. In total, we undertook diving surveys at 11 sites between April and October 2010. Fig. 1 shows the location of each site and

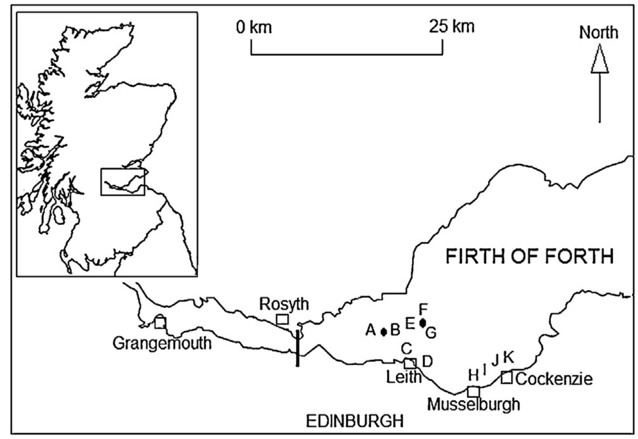

Fig. 1. Field sites in the Firth of Forth. Sites A–I were identified from Fulton's surveys in 1895 (Fulton 1896). Sites J and K were identified from an 1852-56 Firth of Forth Admiralty chart.

Table S1 (see Appendix) provides location coordinates; transect bearings and depth of seabed at chart datum for these.

Fieldwork methods

Fieldwork took place between April and October 2010. A team of four divers performed two dives at each site. One pair performed in situ quadrat analysis of the benthic habitat, while the second pair took a sediment core sample for shell community analysis. We used 50 m transects for benthic community analysis. Transects either followed the direction of dredge surveys conducted by Fulton (1896), or went between chart soundings (e.g. where the word 'oyster' was shown on the chart). Ten 1 m^2 quadrats were randomly selected on either side of the tape along the transect for in situ analysis. Site D had to be omitted from the analysis as no quadrat data were obtained due to strong currents and low visibility.

During the second dive, the two divers randomly selected a position to take a sediment core within 2 m of the start of the previously used transect. The core consisted of a 2 m long, 10 cm diameter PVC tube, with teeth cut into one end to facilitate penetration into the sediment. Our methodology for this procedure was based closely on Edgar and Samson (2004) and went as follows: the tube was held upright on the seabed using a long handled-clamp bolted together with wing nuts, once the tube was in position divers forced it into the sediment using a modified post-driver. Once driven into the sediment a sealed cap was placed on top of the core to allow it to be pulled out of the seabed with minimal loss of sediment. As soon as the corer was pulled out a second cap was secured on the base and a rope deployed allowing up-right recovery to the boat. The corer was kept upright until it was taken onto land where the seawater was siphoned off. The core was then extruded and split longitudinally using a thin metal wire to minimise contamination of sediment. One half of the core was used for isotopic dating analysis, the other for shell community analysis.

Benthic community analysis

We analysed quadrats in situ and recorded the substrate type (e.g. percentage cover of mud, broken shell) and presence of live and dead shells (both percentage cover and number). Epifauna were identified to species or to family if further identification was not possible. For shell community analysis, each core was split into 5 cm-long sections and rinsed using a 1 mm sieve to leave only mollusc shells behind. These shells were then separated into those that were identifiable and those that were too fragmented to be